

Experimental Attempts at Encouraging Eucalypt Regeneration in Non-Native Pastures of Northern Victoria and Central Western NSW

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This paper reports the results of three “cartwheel-type” regeneration experiments around woodland eucalypt trees (*Eucalyptus melliodora* and *E. albens*). In each experiment treatments such as scalping (removal of topsoil) and applying herbicides were applied to plots radiating from the trunk of a tree and were replicated in each of the four main compass directions. Scalping at Mansfield and herbicide/mowing at Panuara, resulted in significantly higher numbers of seedlings but spatial variability in the amount of regeneration around the trees was also observed with seedlings more common on the southern sides of trees. The conventional explanation for this, viz. unequal seed dispersal due to direction of prevailing winds, does not adequately explain the results. It is suggested that habitat factors, such as differences in shading or topsoil moisture, may offer a better explanation — at least in seasons which are less than optimal for regeneration. Regeneration did not occur in every season despite the apparent receptivity of seedbeds. The results suggest that if seedfall is adequate and a receptive seedbed is present, then above-average spring and December rainfall, together with at least 80 mm of rain in January, February or March, are necessary for successful spring/summer recruitment. Climatic conditions were suitable for regeneration at Mansfield (Victoria) and Panuara (NSW) in 1992/93. One year old scalps were associated with the highest number of seedlings at Mansfield but newly-prepared scalps at Panuara were associated with the least number of seedlings during the same season. Possible reason for these results are discussed.

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KEYWORDS: *Eucalyptus albens*, *Eucalyptus melliodora*, recruitment, shade, scalping, rainfall, glyphosate.

INTRODUCTION

The case for re-establishing trees and shrubs in the rural environment has been put forward by many authors, including Beckmann and Davidson (1990), Bird et al. (1992) and Dalton (1993), and will not be repeated here. Tree and shrub establishment technology has improved remarkably in recent years. As a result of research in southern Australia, e.g. by C.V. Malcolm in Western Australia, G. Dalton in South Australia and P.R. Bird in Victoria, reliable direct seeding techniques are now available for rural lands (Dalton 1993). Aerial seeding of eucalypts has also been successfully practised on mined sites in areas with predictable seasonal rainfall (e.g. Foster 1985) and some success with simulated aerial seeding on rural lands was reported by Campbell and Nicol (1996).

Natural regeneration has been the basis of forest regeneration following logging for many years (Florence 1996) and seed production and regeneration requirements of most commercial forest eucalypts are reasonably well known (e.g. Boland et al. 1980, Cremer et al. 1990). In rural areas, however, natural regeneration has been limited by grazing, cultivation and competition from pasture species for over a century and many of

the remaining trees are very old (Middleton 1984, Campbell et al. 1988). Regeneration is dependent on the chance occurrence of heavy seedfall, high soil moisture and suitable temperatures for germination (Venning 1988) as well as a favourable weed-free seedbed. Curtis (1990) estimated that these conditions occurred only once every 10 to 20 years in the Northern Tablelands of NSW. Attempts at encouraging natural regeneration in rural areas have been disappointing but unplanned occurrences do occur (Venning 1988, MacLennan et al. 1992). In the higher rainfall country of South Australia, natural regeneration was associated with low feral animal populations, low grazing pressure by domestic animals, the presence of scattered trees, lack of 'pasture improvement', and above-average rainfall for two consecutive years (Venning 1985).

Reducing herbage competition, e.g. by cultivation and applying herbicides prior to expected seedfall, and controlling grazing following emergence, have been suggested as ways of enhancing regeneration (Venning 1988, Curtis 1990, Cremer et al. 1990). Venning (1988) also suggested concentrating efforts on situations where regeneration was more likely such as around species known to be good regenerators, e.g. *Eucalyptus camaldulensis*, where exotic pastures are absent, and on the leeward side of tree clumps. Until reliable techniques for promoting natural regeneration in woodlands have been developed, infrequent occurrences of regeneration can be protected, e.g. as was reported by Semple (1987). In some areas regeneration may already be present in the form of suppressed lignotuberous seedlings, which can be encouraged by altering the grazing regime (Curtis 1990, Cluff and Semple 1994).

Unlike commercial forest species, recruitment processes in woodland eucalypts are poorly understood (Venning 1988). Some progress on flowering, seedfall, seed predation and/or emergence processes has been made in recent years for *Eucalyptus salmonophloia* F. Muell. (e.g. Yates et al. 1996), eucalypts of the Northern Tablelands of NSW (Curtis 1989, 1990), some tropical woodland eucalypts (Setterfield and Williams 1996) and some eucalypts of the Central West of NSW (Semple and Koen 1997). In the last-mentioned study of eucalypt emergence and survival on differently prepared seedbeds, it was found that no particular seedbed was consistently associated with high numbers of emergents. The authors suggested that the main effect of seedbed preparation was in controlling exotic herbage competition during the eucalypt seedling's first year.

The aim of the experiments described below was to evaluate the role of seedbed type on eucalypt emergence and survival around actual trees, rather than in small plots divorced from the woodland situation. As with Semple and Koen's (1997) study, seedbeds were prepared in understories dominated by exotic species, which are common in the winter rainfall zone of south-eastern Australia. Unlike the former study, however, these experiments were designed to detect effects of the presence of the parent tree on emergence/survival, where seed supply was not controlled, although it was monitored in one of the experiments. The species selected for the experiments, yellow box (*Eucalyptus melliodora* Cunn. ex Schauer) and white box (*E. albens* Benth.), are common woodland species of the inland slopes of south-eastern Australia.

METHODS

A common feature of the three trials was the imposition of a range of treatments in plots that radiated out in a "cartwheel" fashion from the trunk of a relatively isolated tree (e.g. Figure 1). Each seedbed treatment was repeated in each of four quadrants as defined by the main points of the compass. In each study it was believed that fruits on the trees selected would shed seed during the period of the trial. All trial areas were fenced to exclude domestic stock. Climatic and other data for the three trial sites are presented in Table 1 and Figure 2. As the Mansfield trial was carried out independently of the other two, there were some differences in the methods used.

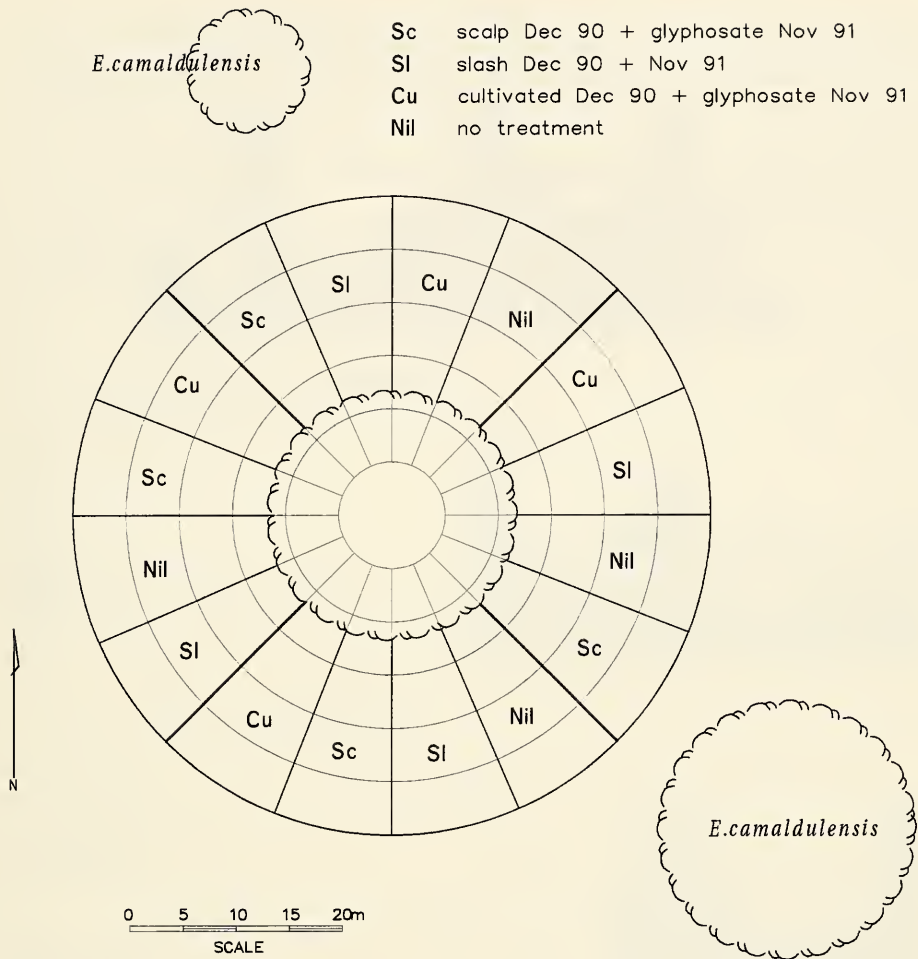


Figure 1. "Cartwheel" layout of treatments at the Mansfield site.

Mansfield (Dec. 1990 to May 1994)

This experiment was located 9 km west of Mansfield in the foothills country of north-eastern Victoria. The area around an isolated *Eucalyptus melliodora* tree was divided into four quadrants: NW-NE, NE-SE, SE-SW and SW-NW. Each quadrant was subdivided into four plots extending 30.5 m from the centre of the trunk of the tree (Figure 1) and the following treatments randomly allocated to the 5.5–30.5 m zone in early December 1990: scalping — removal of the top 3 cm of soil; slashing and removal of slashed material; cultivation to a depth of 10 cm with a rotary hoe; and control — no treatment.

As no seedlings were evident by early November 1991, a further set of treatments was imposed such that overall treatments were: scalping Dec. 1990 and glyphosate at 2 L/ha in Nov. 1991; slashing Dec. 1990 and Nov. 1991 and removal of slashed material; cultivation Dec. 1990 and glyphosate at 2 L/ha in Nov. 1991; and control — no further treatment.

TABLE 1
Brief details of trial sites

	Mansfield	Panuara	Molong
Elevation (m)	335	580	540
Mean annual rainfall(mm)	717 (Mansfield PO)	748 ('Weemalla')	705 (Molong)
Land use (grazing by:)	sheep & cattle	sheep	sheep
Pasture	perennial ryegrass, sub. clover and other introduced annuals	introduced annuals	phalaris, sub. clover and other annuals
Slope (%)	4-5	8-13	4-14
Aspect	north-east	west	Tree 'A' (east) Tree 'B' (west)

Panuara (Oct. 1992 to Feb. 1995)

This experiment was located 30 km south-west of Orange in the Central Tablelands of NSW. Relatively isolated *E. melliodora* trees were again the subject of investigation. Selection of trees was constrained by the small size of the ungrazed paddock. Hence, truly isolated trees were difficult to obtain. One tree and half of the area around two other trees were selected and treatments imposed on radiating plots as before, except that quadrants were bounded by the cardinal points of the compass, i.e. N-E, E-S, S-W and W-N. Plots extended for 9.5 to 10 m beyond the mean canopy radius of each tree.

The following treatments were randomly allocated to one of five plots in each quadrant in late 1992: scalping — removal of the top 10 cm of soil (Nov.); glyphosate at 1 L/ha (early Oct.)/slashing (mid Oct.); glyphosate at 1 L/ha (early Oct.)/slashing (mid Oct.)/fluazifop-p, a grass-selective herbicide, at 4.3 L/ha (Jan. 1993); glyphosate at 1 L/ha (early Oct.)/slashing (mid Oct.)/fluazifop-p at 4.7 L/ha + simazine, a residual herbicide, at 3 L/ha (Feb. 1993); and control — glyphosate at 1 L/ha (early Oct.).

A preliminary examination of seedling numbers suggested that seedlings were not evenly distributed around trees — an effect which may have been due to summer shading. Shading on the treated area around each tree was mapped hourly on a cloudless day at Panuara in midsummer (14 Jan. 96) and at Mansfield in late summer (15 Feb. 96). Due to differences in mapping scales, timing of observations, diameters of treated areas, aspect, slope, as well as the confounding influences of surrounding trees, it was not possible to directly compare results at the two sites, nor to analyse them in the same way.

Molong (Aug. 1993 to Feb. 1995)

The experiment area was 9 km west of Molong near the western margin of the Central Tablelands of NSW. The circular area around two isolated *Eucalyptus albens* trees was subdivided into four quadrants: NW-NE, NE-SE, SE-SW and SW-NW. Each quadrant was subdivided into three plots extending 5 m beyond the mean radius (6.6 m and 8.5 m) of the canopy of each tree. Glyphosate was applied at about 2 L/ha to all plots in mid Aug. 1993 and to any missed areas in early Sep. 1993.

One of the objectives of this trial was to evaluate the effects of staggered monthly follow-up applications of glyphosate until germination seemed imminent, i.e. when seed-fall and rainfall coincided. Treatments were randomly allocated within each quadrant as follows: follow-up glyphosate one month (late Sept. 1993) and four months (mid Jan.

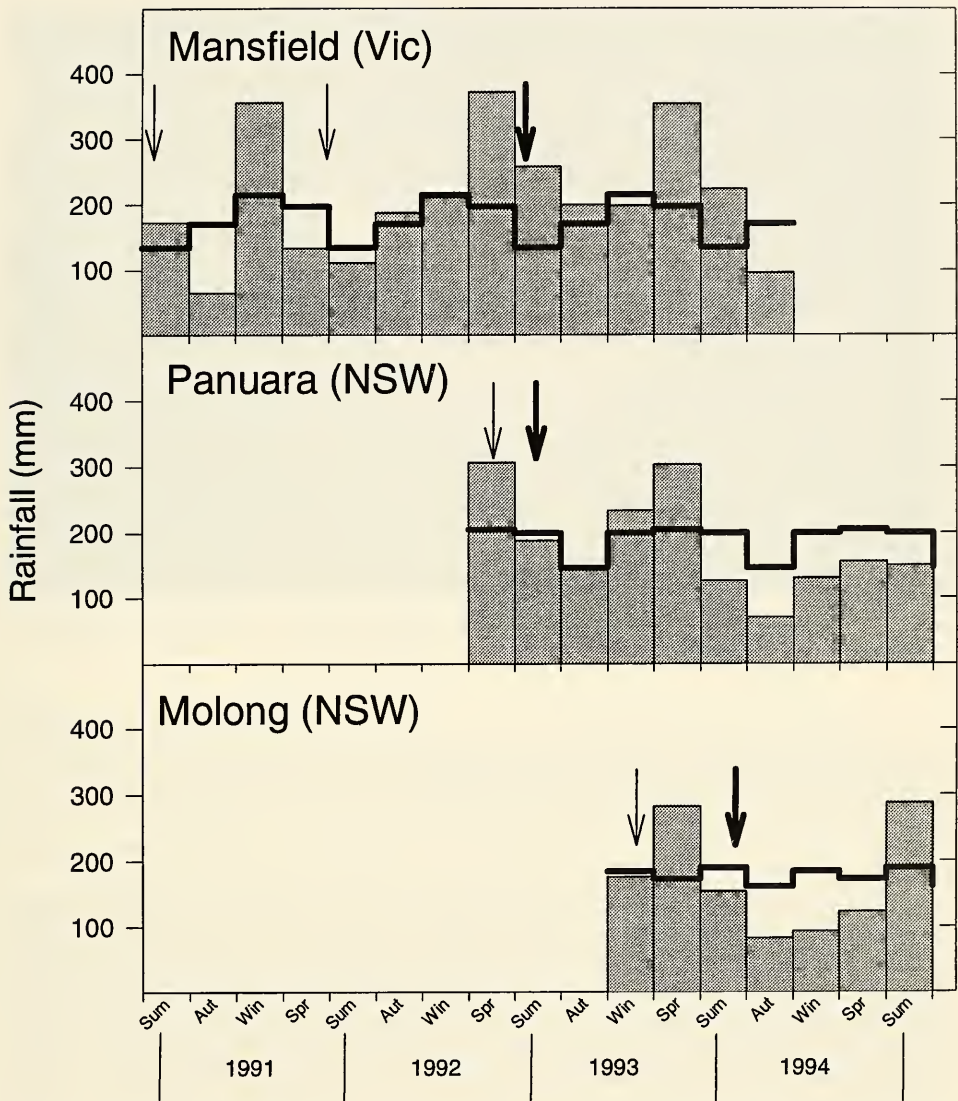


Figure 2. Seasonal rainfall (mm) at the three sites during the periods of the trials. Thickened lines indicate long term means at Mansfield (1901–93), “Weemalla”, Panuara (1971–92) and Molong (1884–1993). Thin arrows indicate the commencement of treatments (and retreatments at Mansfield) and thick arrows indicate the first occurrence of seedlings at each site.

1994) later; follow-up glyphosate two months later (early Nov. 1993); and follow-up glyphosate at three months later (mid Dec. 1993).

The second objective of this experiment was to monitor some factors thought to be responsible for recruitment. Circular 0.25 m² seed collectors (Figure 3) were installed at the edge of the canopy around both trees and monitored at approximately weekly intervals. Two collectors were located in north and south positions at one tree (‘A’) and four at north, south, east and west positions at the other (‘B’). Maximum/minimum temperatures,



Figure 3. A simple cloth mesh (2125 LaCoste fabric manufactured by Petlee P/L) seed collector at Molong. A stone was placed in the bottom of the collector to prevent its being disturbed by wind.

as recorded by a shielded thermometer in the canopy 4.5 m above ground level, and also at the nearby homestead, were recorded at approximately weekly intervals. Topsoil (0–5 cm) moisture (gravimetric) was measured in all plots in Oct. 1993 and Feb. 1994.

Statistical Analyses

Data from these trials were analysed using analysis of variance techniques, transforming the data by taking natural logarithms where necessary. Data based on treatments applied about a single tree used the compass based quadrants as blocks, necessitating a residual error term based on treatment by quadrants interaction. For sparse data such as from the Panuara trial, a generalised linear model was used under the assumption of a Poisson error distribution and log link function. Treatment means were examined for significant differences ($p = 0.05$) using the protected least significant difference procedure.

RESULTS

Seedlings and Survival

Seedlings of *E. melliodora* (and some of *E. camaldulensis*) were first observed at Mansfield in December 1992, 24 months after initial treatment and 13 months after retreatment. At Panuara, *E. melliodora* seedlings were first observed in January 1993 about 3 months after initial treatment. Only one *E. albens* seedling was observed at Molong, in February 1994, 5 months after initial treatment; this seedling did not survive. In contrast, most of the summer 1992/93 seedlings at Mansfield and Panuara were still present at the end of the second summer (and third summer at Panuara). Further recruitment occurred at Mansfield in summer 1993/94 but it was less marked at Panuara (Table 2).

TABLE 2

Total numbers of seedlings recorded around each tree (across all treatments) at the three trial sites

Site/trees/ times of treatment	Approx. area (m ²) treated	Number of seedlings				
		autumn 1991	autumn 1992	autumn 1993	autumn 1994	late summer 1995
Mansfield (Dec. 1990 & Nov. 1991)	2830	0	0	205	299	—
Panuaara A	1180			83	104+	110†
Panuaara B*	515			10	14+	15
Panuaara C* (Oct. 1992 to Feb. 1993)	450			1	1	1
Molong A	285				0	0
Molong B (Aug. 1993 to Jan. 1994)	345				1	0

* Only half of the area around each tree was treated.

+ Seedlings present in 1994 were of a similar size. It is likely that many of the additional seedlings were missed in the 1993 counts.

† Change from 1994 was due to 9 new seedlings (of which 5 were on scalped plots) and 3 deaths.

— Seedlings not counted

Distribution of Seedlings

For seedling counts at the Mansfield site, plots were subdivided at radial intervals of 5 m. This permitted an assessment of the effect of distance from the tree on seedling numbers. When averaged across treatments, seedling density was significantly ($p = 0.05$) higher at and just beyond the edge of the canopy (Figure 4).

Where all of the area around a tree was treated, directional effects were also apparent (Figure 5) [as treatments were only imposed beyond the edge of the canopy at Panuaara, seedling numbers beneath the canopy at Mansfield have, for comparison purposes, been omitted from this figure]. At Mansfield, the treatment with the highest number of seedlings (scalping) accounted for 72 % of all seedlings and was largely responsible for the distribution shown in Figure 5. As described later, differences between treatments were less marked at Panuaara. However, when the proportions of seedlings are presented in equivalent quadrants to those at Mansfield (though not all treatments are now equally represented in each quadrant), a similar pattern for the north and south quadrants emerged — but proportions in the east and west were reversed. Due to the lack of replication at either site, the statistical significance of these patterns cannot be quantified, but a higher proportion of seedlings in the south is strongly suggested.

Shading of Plots

At Panuaara, the area of each plot which was continuously shaded between the hourly observations was estimated using grid squares. These were summed and divided by plot area to give 'full plot shade hours' for each plot (Figure 6A).

A simpler procedure was used for the Mansfield data. Each of the 13 shade maps was replotted on transparent films, which were then overlaid to provide a map of relative total shading around the tree (Figure 6B). It should be noted that, unlike the Panuaara data, this diagram includes a considerable area beneath the canopy.

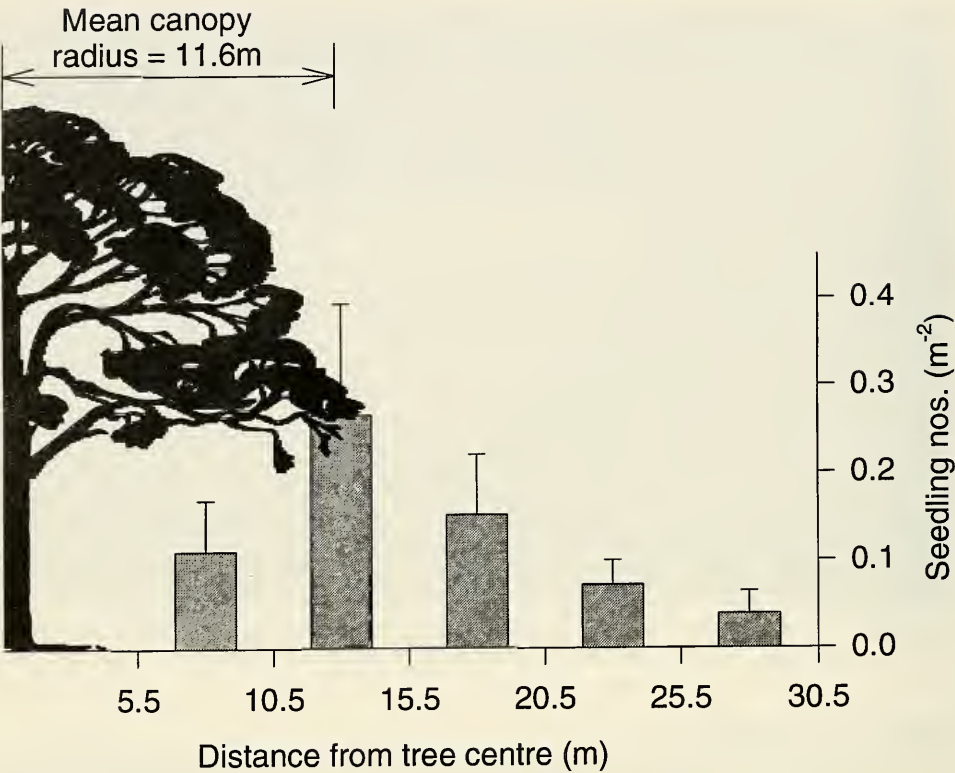


Figure 4. Seedling density around the *E. melliodora* tree at Mansfield in autumn 1994 — direction and treatment effects ignored [Tree silhouette is diagrammatic only].

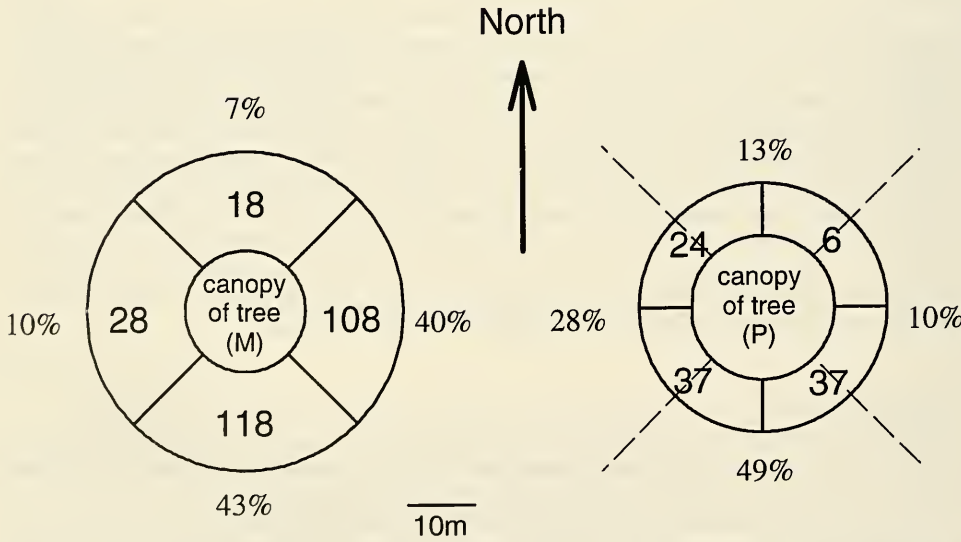


Figure 5. Numbers and proportions of seedlings outside the canopy in each of the four treatment quadrants at Mansfield (M) and Panuara (P) in autumn 1994. For comparison purposes, seedlings under the canopy at Mansfield have been omitted.

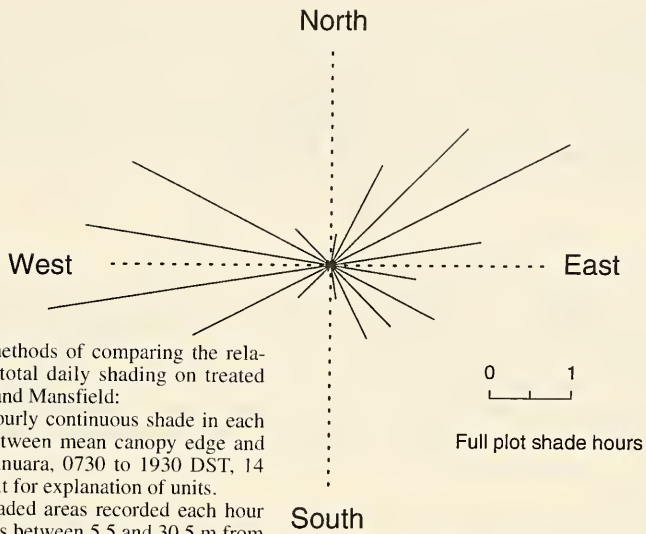
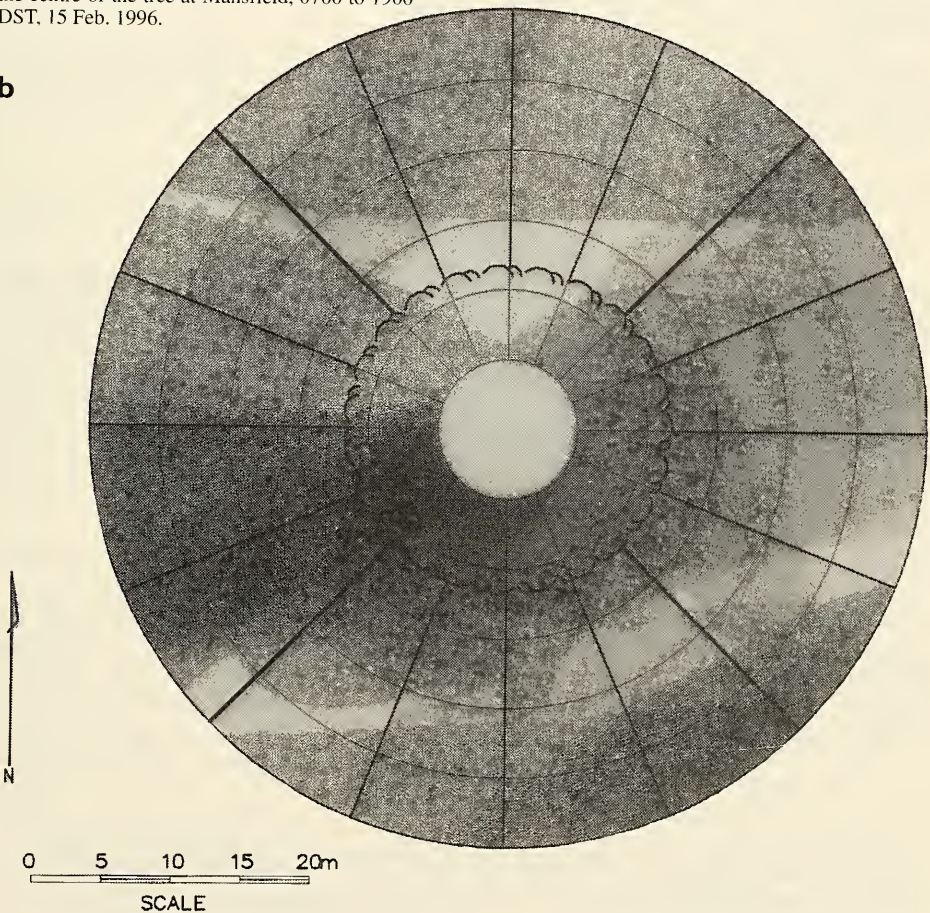
a

Figure 6. Two methods of comparing the relative amounts of total daily shading on treated areas at Panuara and Mansfield:

A. Cumulative hourly continuous shade in each treatment plot between mean canopy edge and 10 m away at Panuara, 0730 to 1930 DST, 14 Jan. 1996. See text for explanation of units.

B. Overlay of shaded areas recorded each hour in the treated areas between 5.5 and 30.5 m from the centre of the tree at Mansfield, 0700 to 1900 DST, 15 Feb. 1996.

b

At Panuara in midsummer, plots in the north-east and west received the longest period of shading. Comparison of data in Figures 5 and 6A, however, suggested that midsummer shading and numbers of seedlings were unrelated (Rank correlation = 0.33).

The qualitative Mansfield data in Figure 6B also showed considerable shading in the east and west but with increased shading (compared to the data collected a month earlier in Fig. 6A) in the south — consistent with the apparent northerly movement of the sun following the summer solstice.

Seedbed Treatments

Sufficient numbers of seedlings were present only at Mansfield and Panuara (one full tree and one half-tree) for an adequate analysis of treatment effects. Results are presented in Table 3. The scalp treatment was associated with the most seedlings at Mansfield but with the least seedlings at Panuara. Regeneration was almost immediate in all treatments except scalped plots at Panuara, whereas two years elapsed before it was evident on scalped (and other plots) at Mansfield. Though subsequent recruitment was low at Panuara, it did not occur on scalped plots until some two years after the initial treatment (Table 3).

Regeneration occurred in the other three treatments at Mansfield but seedling numbers were lower than in the scalped plots and not significantly different from each other (Table 3).

At Panuara, seedling numbers (Table 3) were significantly higher on the glyphosate/slash treatment and were significantly lower on the scalped treatment, compared to the other three treatments. Differences in seedling numbers between the other three treatments were not significant.

TABLE 3
Seedling numbers in each of the seedbed treatments at Mansfield and Panuara

Site	Treatment	Back transformed mean numbers of seedlings per plot*		
		Apr. 93	May 94	
Mansfield (1 tree)	scalp (Dec. 90) + glyphosate (Nov. 91)	25.3a†	39.9a	
	slash (Dec. 90 + Nov. 91)	2.1b	5.0b	
	cultivation (Dec. 90) + glyphosate (Nov. 91)	4.2b	5.6b	
	control — no treatment	1.8b	1.5b	
		Mar. 93	Mar. 94	Feb. 95
Panuara (1½ trees)	scalp (Nov. 92)	0a	0a	0.9a
	glyphosate/slash (Oct. 92)	6.7b	8.0b	8.0b
	glyphosate/slash (Oct. 92) + fluazifop (Jan. 93)	3.3c	4.0c	4.0c
	glyphosate/slash (Oct. 92) + fluazifop/simazine (Feb. 93)	3.7c	4.5c	4.5c
	control — glyphosate (Oct. 92)	1.7c	3.0c	3.3c

* seedling numbers are not comparable between sites due to different plot sizes and methods of analysis

† Means followed by different letters within a site/time subset are significantly different ($p < 0.05$)

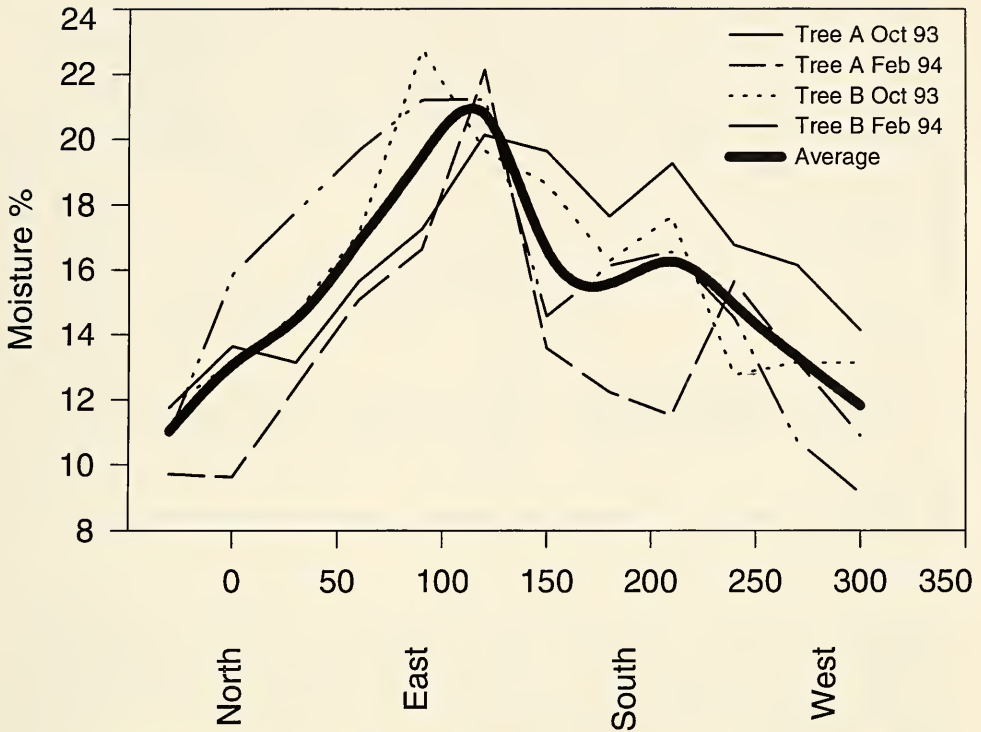


Figure 7. Mean gravimetric 0–5 cm soil moistures, corrected for treatment effects, in radial plots around two *E. albens* trees on two occasions at Molong.

Topsoil Moisture

Moisture (0–5 cm) was measured around the two trees at the Molong site on two occasions — early in the trial (mid Oct. 1993) and shortly after the first summer germinations of herbage were observed in February 1994. No treatment was consistently associated with high or low topsoil moisture levels on either occasion. However, the amount of soil moisture was significantly associated with position around the trees, tending to be higher in the eastern and to a lesser extent, the southern quadrants. Mean soil moistures, with any treatment effects removed, are shown in Figure 7.

Seedfall

Seedfall was measured from early October 1993 to early April 1994 at the Molong site. Only five seeds were collected in the two 0.25m² collectors at tree 'A' — representing a mean 'seed rain' of 0.06 seeds m⁻² day⁻¹ over the 185 day period. At tree 'B', with four collectors, a total of 147 seeds was collected over 198 days. Of a sample of 129 of them, 101 (78.3 %) were germinable. Peak seedfall, up to 3.7 seeds m⁻² day⁻¹, occurred in January/February 1994 (Figure 8). Between early October 1993 and germination in mid February 1994, total seedfall was 116 (c.90 viable) seeds m⁻².

Seedfall and Temperature

Temperature data for the lower canopies of the trees at Molong were incomplete due to occasional storm damage to thermometers. However, maxima/minima recorded at

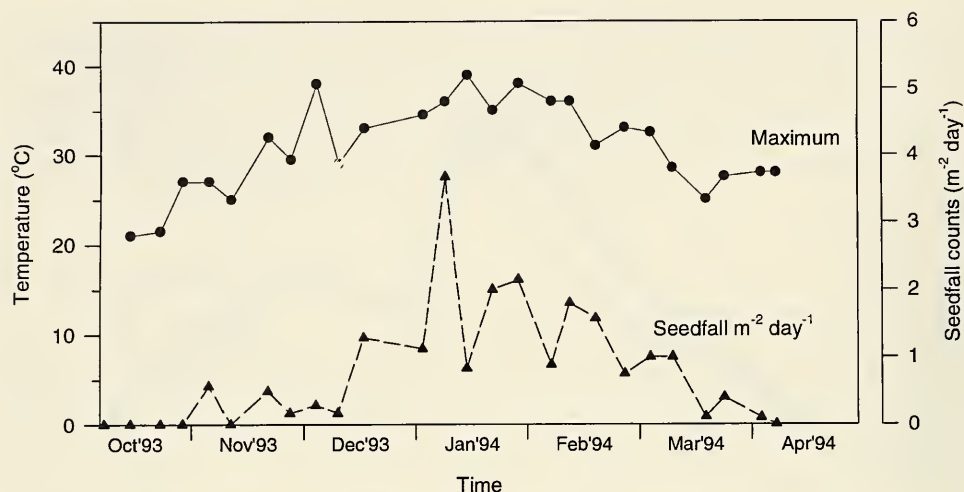


Figure 8. Rates of seedfall at tree 'B' (Molong) and maximum temperature over the same period.

the nearby homestead were highly correlated with those recorded in the canopies, particularly at Tree 'B' where $r = 0.90$ for maxima and $r = 0.93$ for minima. Seedfall at Tree 'B' (where sufficient seedfall data were available) was correlated with maxima recorded at the homestead ($r = 0.66$) but not with minima ($r = 0.38$). Seedfall generally occurred when maxima $> 25^{\circ}\text{C}$ were recorded (Figure 8).

DISCUSSION

As regeneration depends on seed availability, dispersal to safe sites and favourable climatic conditions for germination and establishment, it is difficult to isolate the role of any one factor even in controlled experiments. However, as observations in these experiments were made over a number of years and at different sites, some interpretation is possible.

Seasonal Effects

Curtis (1989) concluded that for successful late spring/early summer recruitment on the Northern Tablelands of NSW, above-average spring to mid-summer rainfall was necessary. Combining data from Curtis (1989) and Semple and Koen (1997) with those from Mansfield, Panuara and Molong (Table 4) indicated that most cases of successful recruitment were associated with above-average spring and December rainfall. If these conditions were satisfied, survival of at least some seedlings was assured provided one month in January, February or March received about 80 mm or more of rainfall.

High pre-germination spring rainfall probably provides sufficient subsoil moisture for survival over summer (Whalley and Curtis 1991). However at Manildra, where simulated seedfall was carried out, the below-average spring 1991 rainfall was supplemented by well above (432% of) average February 1992 rainfall and seedlings established. Germination occurred at "Terrible Vale" and "Birralee" on the Northern Tablelands, but the below-average spring rainfall was not supplemented by sufficient rainfall in January to March and all seedlings died within four months (Curtis 1989).

TABLE 4

Success and failure of eucalypt recruitment in late spring-early summer, together with rainfall, at various sites. At all sites, the seedbed was favourable and seed was available (except perhaps Mansfield in 1991/92). Departures (mm) from mean rainfall are shown in parentheses.

Season	Site	Date seedlings first observed (though they may have been present earlier)	Rainfall (mm)				Established regeneration (i.e. persisting beyond the first summer)	
			Sep. to Nov.	Dec.	Jan.	Feb.		Mar.
1985/86	“Ruby Hills” ¹	Nov. 85	248 (+46)	128 (+40)	97 (-4)	41 (-46)	18 (-49)	Yes
	“Terrible Vale” ¹	Dec. 85	195 (-7)	110 (+22)	64 (-37)	36 (-51)	3 (-64)	No
	“Birrahlee” ¹	Nov. 85	195 (-7)	110 (+22)	64 (-37)	36 (-51)	3 (-64)	No
1990/91	Bathurst ²	Nil	69 (-102)	9 (-51)	48 (-36)	7 (-60)	59 (+4)	No
	Manildra ²	Nil	71 (-78)	5 (-40)	45 (-35)	20 (-45)	26 (-30)	No
1991/92	Manildra ²	Sep. 91 (Sep. sowing) Dec. 91 (Dec. sowing)	129 (-20)	99 (+54)	53 (-27)	281 (+216)	34 (-22)	Yes
1992/93	Mansfield	Nil	133 (-64)	61 (+9)	28 (-16)	22 (-16)	56 (+3)	No
	Mansfield	Dec. 92	372 (+175)	120 (+68)	70 (+26)	68 (+30)	95 (+42)	Yes
	Panauara	Jan. 93	306 (+101)	125 (+73)	31 (-54)	32 (-30)	81 (+44)	Yes
1993/94	Mansfield	May 94	354 (+157)	75 (+23)	28 (-16)	120 (+82)	25 (-28)	Yes
	Panauara	Nil (?)	303 (+98)	18 (-34)	17 (-68)	90 (+28)	47 (+10)	Negligible
	Molong	Feb. 94	282 (+110)	19 (-44)	12 (-57)	122 (+65)	47(-9)	No

¹ Northern Tablelands of NSW sites from Curtis (1989): *Eucalyptus caliginosa* Blakely & McKie ("Ruby Hills" and "Terrible Vale"), *E. stellulata* Sieber ex DC ("Birrahlee"). Only sites where a favourable seedbed, i.e. herbicided, was present have been listed (D.J. Curtis, pers. comm.)

² From Semple & Koen (1997). Seed of woodland eucalypts was surface-sown on small plots in September and December in 1990/91 and 1991/92 (Bathurst 1991/92 data excluded due to apparent loss of seedlings by wingless grasshoppers)

As most eucalypts can germinate over a wide range of temperatures (Venning 1988), it was unlikely that temperature was limiting in spring-summer in the woodland environment. But as high temperature and associated soil drying are responsible for heavy losses of unprotected new seedlings in forests (Florence 1996), any factors moderating high temperatures would be expected to enhance survival of late spring and summer emergents.

Effect of Seedbed

The 1992/93 season was clearly advantageous for regeneration of *E. melliodora*. Even ungrazed controls, viz. glyphosate in mid spring at Panuara and untreated at Mansfield, produced some seedlings. Scalping (+ glyphosate 11 months later) was the most effective seedbed at Mansfield, whereas at Panuara, glyphosate followed by slashing was associated with the highest number of seedlings after one year.

Surprisingly, scalping was the least effective treatment at Panuara. Possible reasons for this apparently anomalous result were: (a) at the time of emergence, the scalp treatment at Mansfield was two years old and herbicide had been applied to remove limited herbage growth. In contrast, the scalps at Panuara were newly-prepared when emergence occurred in the other treatments; (b) slope was higher at Panuara than at Mansfield (Table 1) and a greater depth of soil was removed at Panuara than at Mansfield.

The reason for regeneration failure at the Mansfield site in the first (1991/92) season was uncertain, though it was probably due to inadequate rainfall. At Panuara, seasonal conditions were favourable in 1992/93, yet seedlings did not appear on scalped plots (which remained relatively bare) until some time between March 1994 and February 1995 (Table 3), despite poor seasonal conditions during this time.

These results suggest that scalped areas require a 'settling in' period — perhaps due to enhancement of roughness by litter accumulation or by limited herbage growth. This would probably be more important on land of higher slope. The necessity of some 'vegetative roughness' for successful aerial seeding of exotic pasture species on infertile sites, and for simulated aerial seeding of eucalypts, has been observed by Campbell (1996) and I. Higgins (DNRE Victoria, pers. comm.) respectively. Vegetative mulches also have other benefits such as reduced evaporation and increased rainfall infiltration (Dalton 1993).

Further support for this suggestion comes from Semple and Koen's (1997) small plot trials where ripping of scalped plots was found to be necessary for retention and germination of surface-sown seed. Although scalping was not associated with the highest number of seedlings initially (compared to other seedbed treatments), it commonly was after one year and was attributed to enhanced survival of initial emergents and the possibility of further germinations on a weed-free seedbed. Excess standing vegetative residue, however, reduced regeneration at Panuara, where significantly ($p = 0.05$) more established seedlings were associated with the glyphosate/slash treatment than for glyphosate alone.

Post-emergence applications of a grass-selective herbicide (fluazifop-p), either alone or in combination with a residual herbicide (simazine), to glyphosate/slashed plots (which had low levels of live herbage at the time) did not enhance survival, but, compared to the glyphosate/slash treatment, significantly reduced it. Although these herbicides were recommended by Bird et al. (1994) for young trees, they were referring to mature seedlings rather than those at the 2 to 4-leaf stage.

The role of pre-germination applications of glyphosate in assisting regeneration, particularly at Panuara, but also noted by others such as Curtis (1989), needs some explanation as it is not always successful. Applying herbicide around trees commonly fails to promote regeneration because of lack of seed and/or an unfavourable season, such as occurred at the Molong site in 1993/94. Even when these conditions are satisfied and

germination occurs, survival may be low or negligible as was the case in many of the seedbed trials (direct drilled and surface-sown) reported by Semple and Koen (1997). Survival after one year in these trials was generally higher on the scalped treatments than on any of the others, including herbicide. The poor performance of the non-scalp treatments was attributed to the rapid recolonisation of plots by weeds. It was suggested that if treatments had been delayed until later in the season, better weed control may have been achieved. The success of glyphosate at Panuara can probably be attributed to the late application (October — due to earlier wet weather) and the reduced frequency of summer weeds at the site.

Seedfall

Only one of the two *E. albens* trees at the Molong site consistently produced enough seed for adequate analysis. Peak seedfall occurred in January 1994 when up to 3.7 seeds $\text{m}^{-2} \text{day}^{-1}$ were recorded. This declined steadily until April when observations ceased. This pattern of seedfall was consistent with observations of other eucalypt species on the Northern Tablelands of NSW by Curtis (1989), who also noted that regeneration was commonly associated with the 'rising limb' of the seedfall graph, rather than at its peak.

The reasonable correlation between the rate of seedfall and maximum weekly temperature, was not unexpected. However, as dehydration is largely responsible for seed release in eucalypt fruits (Christensen 1971, Boland et al. 1980), low humidity, which would be expected to be associated with higher temperatures in non-coastal areas, was probably the operative factor.

Although the rate of seedfall was not high, it was comparable to that associated with successful recruitment in the Northern Tablelands. Here, Curtis (1989) reported that 100 to 200 seeds m^{-2} in the six months prior to germination appeared to be necessary. [It is perhaps not coincidental that a similar number of seeds is also considered desirable for aerial seeding of phalaris (M.H. Campbell, NSW Agriculture, pers. comm.)]. About 90 viable seeds m^{-2} were recorded in the four months prior to germination at Molong. However, only one seedling was recorded (in the SSE) following above-average rainfall in February 1994 but it only survived a few months of below-average rainfall.

Distribution of Seedlings

According to Cremer et al. (1990), the direction/speed of dry season winds is the main factor affecting seed dispersal of forest eucalypts. Most seed falls within a distance of $1\frac{1}{2}$ x height of parent tree, though isolated trees can have a higher proportion of seed beyond this limit than do trees in a forest. In the studies reported here, the treated area did not extend as far as $1\frac{1}{2}$ x height of parent. At Mansfield seedlings were recorded up to 30 m from the 33 m high parent which was consistent with Curtis' (1989) observation of seedlings up to 13 m from an 18 m high woodland eucalypt on the Northern Tablelands. Also consistent with Curtis' observations was that the highest density of seedlings at Mansfield occurred near the edge of the canopy. As most of the seed falls in this region (Cremer et al. 1990), these observations suggest that the quantity of seed is one of the major factors affecting recruitment. Though only a very small proportion of viable seed (e.g. 0.16%, Curtis 1989) results in established seedlings, studies by O'Dowd and Gill (1984) indicate that large quantities are needed so that some seed remains after seed-harvesting ants are satiated. If this is the case, then emergence would be almost wholly a function of the co-occurrence of suitable rainfall, receptive seedbed and seed (i.e. seed supply > losses due to ant theft or other causes). According to this model, the asymmetrical distributions of seedlings around parent trees would be solely due to wind direction at the time of seedfall.

The tendency for seedlings to be more common on the southern sides of trees — noted at Panuara and Mansfield, and also by Curtis (1989) — may have been due to dry northerly winds depositing more seed in the south, but in the absence of seed dispersal and wind data this hypothesis cannot be tested. Curtis (1989) concluded that best recruitment occurred just outside the canopy on the southern side of trees. In one experiment where eucalypt seed was sown (and hence, independent of wind-dispersed seed) in three locations: amongst trees, in the open and on the southern side of tree clumps, 'the plots on the southern sides of the clump of trees had twice as many recruited seedlings than those directly under trees and six times as many as the open plots' (p.108). He suggested that protection from frost and desiccation may have been responsible for this result.

A higher density of seedlings on the southern sides and beneath the canopies of *Eucalyptus pauciflora* Sieber ex Sprengel trees was also noted in the Orroral Valley near Canberra. According to Egerton (1996), this could be explained by warmth provided by the canopy at night and protection from direct winter-morning sunlight, which can cause frost-induced photoinhibition in seedlings. Seedling deaths due to 'frost heave' have also been reported (Cremer 1990) in cold climates. However, frost effects were unlikely to explain seedling distribution at Panuara and Mansfield, where asymmetry was established well before frost damage could occur; and very few deaths were recorded over winter.

Mid January shading at Panuara (Figure 6A) was not correlated with seedling numbers. However, at Mansfield in mid February, increased shading in the south was evident (Figure 6B). Importantly, this pattern would be equivalent to that two months earlier, in mid December, when seedlings were first appearing. It is likely, therefore, that protection from the increasing levels of radiation of late spring/early summer allowed more seedlings to survive.

Glasshouse trials by Curtis (1989) showed that increased frequency of watering of eucalypt seeds sown at shallow depth significantly increased emergence. Under field conditions, prolonged periods of wet weather would be expected to yield a similar result. Similarly, any factor, perhaps shading, which reduces the rate of topsoil drying would be expected to enhance emergence. Topsoil moisture data at Molong (Figure 7) suggested that the rate of drying was reduced on the eastern and southern sides of a tree. This may be critical to emergence in seasons when topsoil moisture is limiting.

Woodland eucalypts in the subhumid zone of south-eastern Australia have been in decline for many years and lack of natural revegetation (due to grazing, sowing exotic pasture species and soil cultivation) has been cited (Nadolny 1995) as a major cause. These experiments have confirmed the importance of grazing (as evidenced by the lack of seedlings outside exclosures) and the presence of exotic pasture species as limiting factors. Some forms of cultivation, however, may enhance recruitment as also reported by Dalton (1993) and MacLennan et al. (1992). Seedfall from parent trees was not limiting in most cases but the importance of rainfall and climate modification afforded by the presence of existing trees in promoting recruitment has been highlighted.

CONCLUSIONS

The results of the experiments indicate that eucalypt recruitment in woodlands with non-native pastures can be enhanced by an appropriate seedbed, adequate seedfall (i.e. abundant fruits), stock exclusion and most importantly, above-average rainfall.

An appropriate seedbed is one that has abundant bare ground, at least during early establishment, and some roughness in the form of vegetative residues. Both slashing/knockdown herbicide and scalping can satisfy these requirements, though the latter appears to need a 'settling-in' period (probably to allow some vegetative roughness to develop) to be fully receptive.

Above-average rainfall in spring and December plus a follow-up of at least 80 mm in January, February or March appears to be required. Well above-average rainfall in the latter months can compensate for lower rainfall in spring but above-average rainfall in December appears to be critical.

The limited seedfall data from one *E. albens* tree supported Curtis' (1989) observation of a summer seedfall peak in other woodland eucalypts. However, successful recruitment appears to be associated with the 'rising limb' of the seedfall graph rather than at the peak. Seedbed preparation as late as November enhanced natural regeneration in the two successful cases reported here.

Limited evidence from these experiments and from other sources suggests that the area near the canopy on the southern side of trees is likely to be the site of maximum recruitment. Although this could be due to the presence of more wind-dispersed seed in this area, it is likely that environmental factors such as increased shading or enhanced soil moisture may be responsible. In favourable seasons, these factors may be of lesser importance.

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